Atmospheric Boundary Layer

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Atmospheric Boundary Layer Definition

"We can define the boundary layer as that part of the troposphere that is directly influenced by the presence of the earth's surface, and responds to surface forcings with a timescale of an hour or less."

Atmospheric Boundary Layer Definition

These forcings include:

- frictional drag
- evaporation and transpiration
- heat transfer
- pollutant emission
- terrain-induced flow modifications

Stull, R. B., 1988: *An Introduction to Boundary Layer Meteorology*. Kluwer Academic Publishers, Boston, MA.. 666 pp.

Atmospheric Boundary Layer Introduction

- Where "The Rubber hits the Road"
- The layer in which we live and do business
- Almost all sensible weather occurs within the boundary layer
- All exchanges of heat, moisture, and momentum between the earth's surface and the atmosphere are modulated by, and take place within, the boundary layer

Atmospheric Boundary Layer Introduction

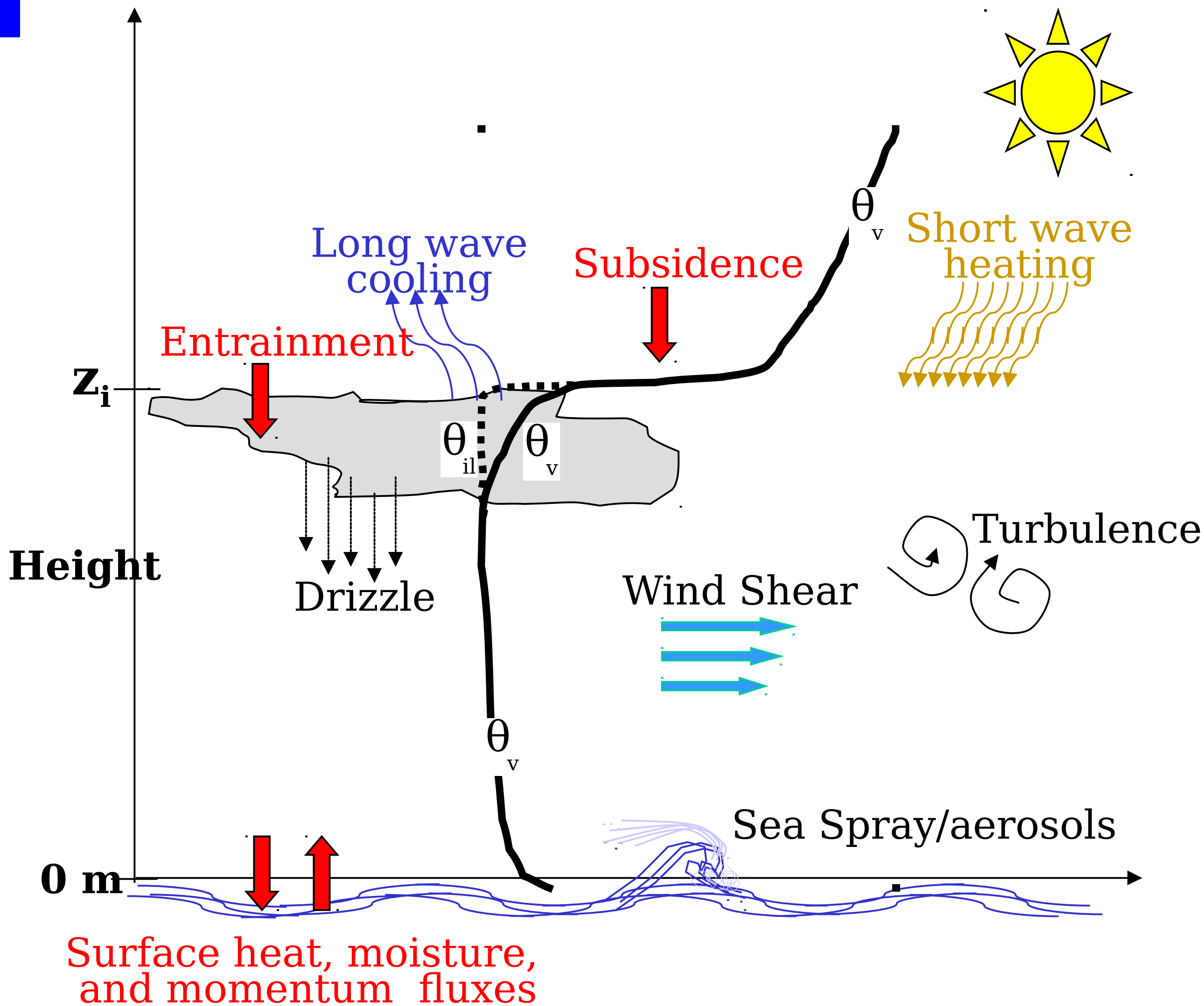
- The depth of the boundary layer is quite variable
- Generally from ~100 m to 3 km
- Over land, the depth varies diurnally and due to subsidence and synoptic forcing
- Over the ocean, depth varies with the presence of clouds, subsidence, and synoptic forcing

Atmospheric Boundary Layer Introduction

Navy Operational Significance

- Ocean thermal structure and underwater acoustics
- Gustiness
- Surface wave generation
- Effects on electromagnetic and optical refractivity
- Fog/low clouds impacts on ceiling and visibility

Stratus-topped Marine Boundary Layer



Atmospheric Boundary Layer Turbulence

- Turbulence is an irregular motion which in general makes its appearance in fluids when they flow past solid surfaces or when neighboring streams of the same fluid flow past one another - *G. I. Taylor and T. von Karman*
- Turbulent fluid motion is an irregular condition of the flow in which various quantities show random variations of time and space coordinates, so that statistically distinct average values can be determined - *Hinze*

Atmospheric Boundary Layer Turbulence

Characteristics of Turbulence:

- Dissipative - “Big whorls have little whorls, which feed on their velocity; and little whorls have lesser whorls, and so on to viscosity.” - L. F. Richardson
- Rotational
- Non-linear
- Diffusive
- Random
- Continuous
- Three-dimensional

Atmospheric Boundary Layer Modeling

The problem:

- To model the evolution of the height and properties of the atmospheric boundary layer given initial properties and sufficient information on the boundaries
- This requires some knowledge of the statistical properties of the turbulence field
- This leads to an additional problem

Atmospheric Boundary Layer Turbulence Closure

A fundamental problem in dealing with turbulence is the closure problem:

- The number of unknowns in the set of equations for turbulent flow is greater than the number of equations
- The equation for the rate of change of wind velocity has terms involving products of turbulent perturbations - second statistical moments
- In deriving prognostic equations for the second moments, third moments are introduced
- This remains one of the unsolved problems of classical physics

Atmospheric Boundary Layer Turbulence Closure

The solution to the closure problem:

- Choose the order of the moment to be explicitly solved for - this leads to the “order” terminology
- Derive parameterizations for the next-higher moments in terms of either mean quantities or lower- order moments
- In order to completely confuse things, Mellor and Yamada (1974; 1982) devised a hierarchy of 4 levels for 2nd order closure models

Atmospheric Boundary Layer Modeling

- The earliest models avoided the problem entirely by merely assuming that the turbulence level is sufficient to maintain a well-mixed boundary layer
- These models are referred to as mixed layer models or slab models
- The entire layer changed as a whole due to heat flux divergence over the layer
- The only values known or specified were at the surface and the top of the layer
- There were no model levels within the layer
- These models fail completely when the boundary layer is stable

Atmospheric Boundary Layer Modeling

First-Order closure:

- The mean quantities are solved for explicitly
- The resulting second moment quantities are parameterized in terms of the mean quantities
- The closure hypothesis is that the fluxes are directly proportional to the gradients of the mean quantities
- There is no tke field
- This is “K-theory”, where K has units of $m^2\ s^{-1}$

$$\overline{w'T'} = K_H \frac{\partial \overline{T}}{\partial z}$$

Atmospheric Boundary Layer Modeling

Second-Order closure:

- The second moment quantities are explicitly solved for
- The resulting third-moment quantities are parameterized in terms of second-moment quantities
- Closure hypotheses are required for each the triple moment terms
- There is now a prognostic equation for tke

Atmospheric Boundary Layer Modeling

In addition to first and second order closure, some "hybrid" models have been developed

- The name 1.5 order closure is often applied to models which have a prognostic equation for tke with first order closure for other second moment quantities
- COAMPS uses a 1.5 order closure scheme (Mellor-Yamada level 2.5)
- Models which have prognostic equations for both tke and tke dissipation are called "e-epsilon" closure models

Atmospheric Boundary Layer Modeling

- Large eddy simulation or LES models are run at extremely high vertical and horizontal resolution so as to explicitly resolve the large turbulent eddies (the smallest scales are parameterized)
- “non-local closure” uses the characteristics of the boundary layer as a whole rather than the local gradients to parameterize turbulence

COAMPS Boundary Layer and Surface Parameterizations

- TURBULENCE:
  - TKE equation
  - Eddy mixing coefficients
  - Length scale
  - boundary layer depth
  - Counter-gradient flux parameterization
  - Effect of clouds
- SURFACE LAYER PARAMETERIZATION
  - Louis scheme
  - Surface fluxes
  - Surface roughness

TKE Equation

The turbulent kinetic energy (TKE) equation:

$$\frac{D}{Dt}\left(\frac{e^2}{2}\right) - \frac{\partial}{\partial z}\left(l e S_e \frac{\partial}{\partial z}\left(\frac{e^2}{2}\right)\right) =$$

$$w'u'\frac{\partial U}{\partial z} - w'v'\frac{\partial V}{\partial z} + \beta g w'\theta'_v - \frac{e^3}{\Lambda_1}$$

The second term on the LHS is the turbulent diffusion of TK
and the terms on the RHS are:

- 1st and 2nd terms are the shear or mechanical productio
- 3rd term is buoyant production of TKE
- 4th term is the dissipation term equal to TKE to the 3/2 po
 over the dissipation length scale

COAMPS Parameterized TKE Equation

$$\frac{D}{Dt}\left(\frac{e^2}{2}\right) - \frac{\partial}{\partial z}\left(K_e \frac{\partial}{\partial z}\left(\frac{e^2}{2}\right)\right) =$$

$$K_M\left(\frac{\partial U}{\partial z}\right)^2 + K_M\left(\frac{\partial V}{\partial z}\right)^2 - \beta g K_H \frac{\partial \theta}{\partial z} - \frac{e^3}{\Lambda_1}$$

The prognostic variable is:

$$\frac{e^2}{2} = u'^2 + v'^2 + w'^2$$

COAMPS Boundary Layer

From the TKE equation, it is evident that the following parameters are of importance in modeling the boundary layer:

- K_e, K_H, and K_M (eddy coefficients for TKE, heat and momentum)
- the turbulent length scale
- depth of the boundary layer
- counter gradient term
- boundary layer clouds (stratus and strato-cumulus) and how they are treated

Eddy Coefficient Formulation

- Early K-theory models used a constant or a prescribed value (cubic polynomial)
- most current models use functions of some "flavor" of the Richardson Number
- COAMPS uses the flux Richardson Number
- The flux Richardson Number is the ratio of buoyant production of TKE to shear production of TKE

$$Ri_f = \frac{{}^{g}\!/_{\theta_v}\, \overline{w'\theta'_v}}{\overline{u'w'}\dfrac{\partial U}{\partial z} + \overline{v'w'}\dfrac{\partial V}{\partial z}}$$

Richardson Number

Vertical Profile

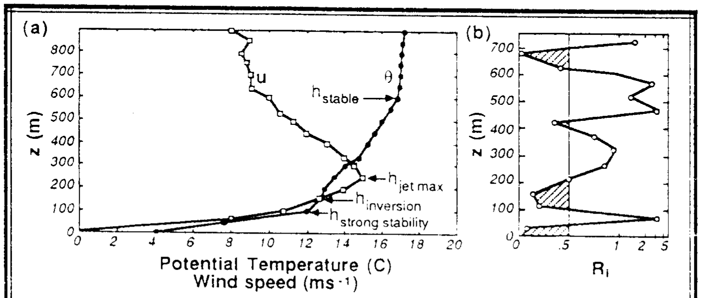


Fig. 12.9 Various depths of the nocturnal boundary layer based on wind and potential temperature for Wangara Day 14 at 0300 LST. (b) Corresponding Richardson number [illegible] After Andre and Mahrt, 1982).

Time-Height Section

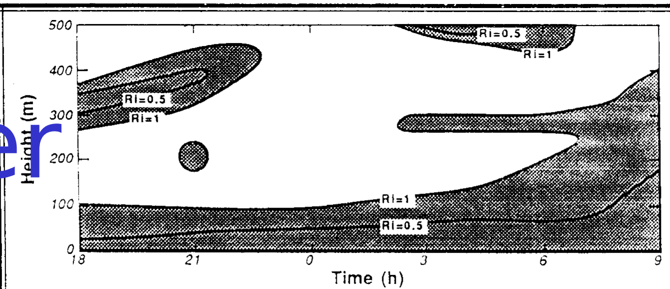
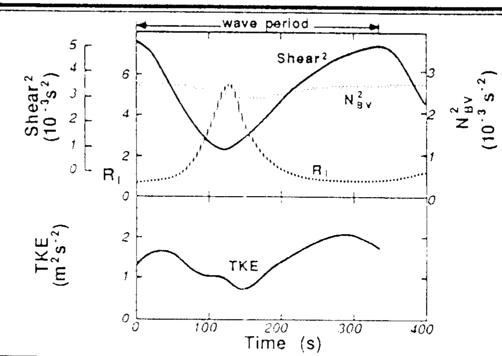


Fig. 5.20 Example of the evolution of local Richardson number with height and time during one night. Regions with Richardson number less than 1.0 are shaded, and are likely to be turbulent. After Mahrt (1981).

Time Series with TKE

Fig. 12.21 Variation of the shear squared, Brunt-Väisälä squared, Richardson number, and turbulence kinetic energy as a function of wave phase. (After Finnigan, et al., 1984).



From Stull (1988

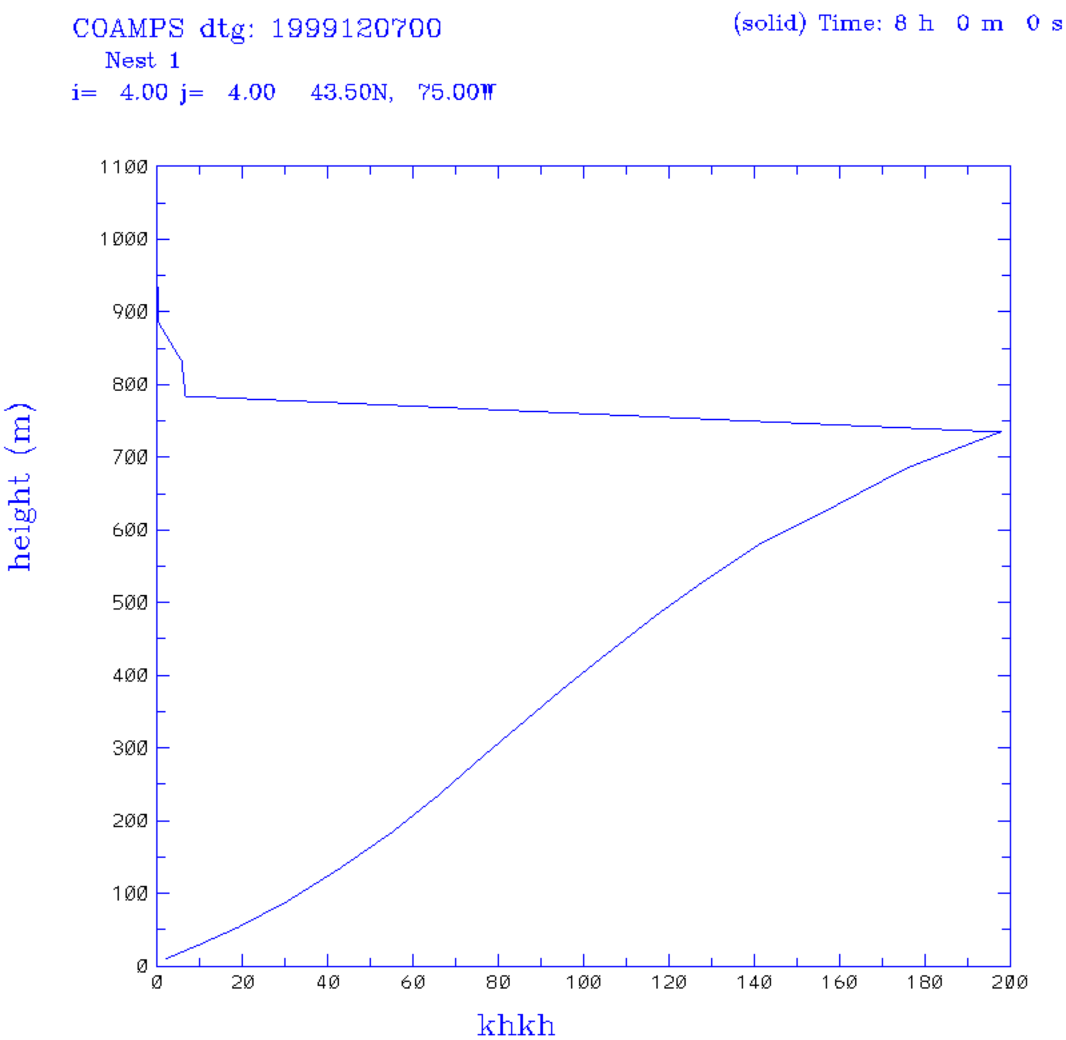
Eddy Coefficient Formulation

- Theoretically, turbulence should occur for $Ri < 0.25$
- Other "flavors" of the Richardson Number are the bulk Ri and the gradient Ri
- In COAMPS, the K formulation is given by a polynomial function of Ri_f multiplied by the length scale and $TKE^{1/2}$:

$$K_{M,H} = S_{M,H} le$$

$$K_e = cle$$

Eddy Heat Coefficient



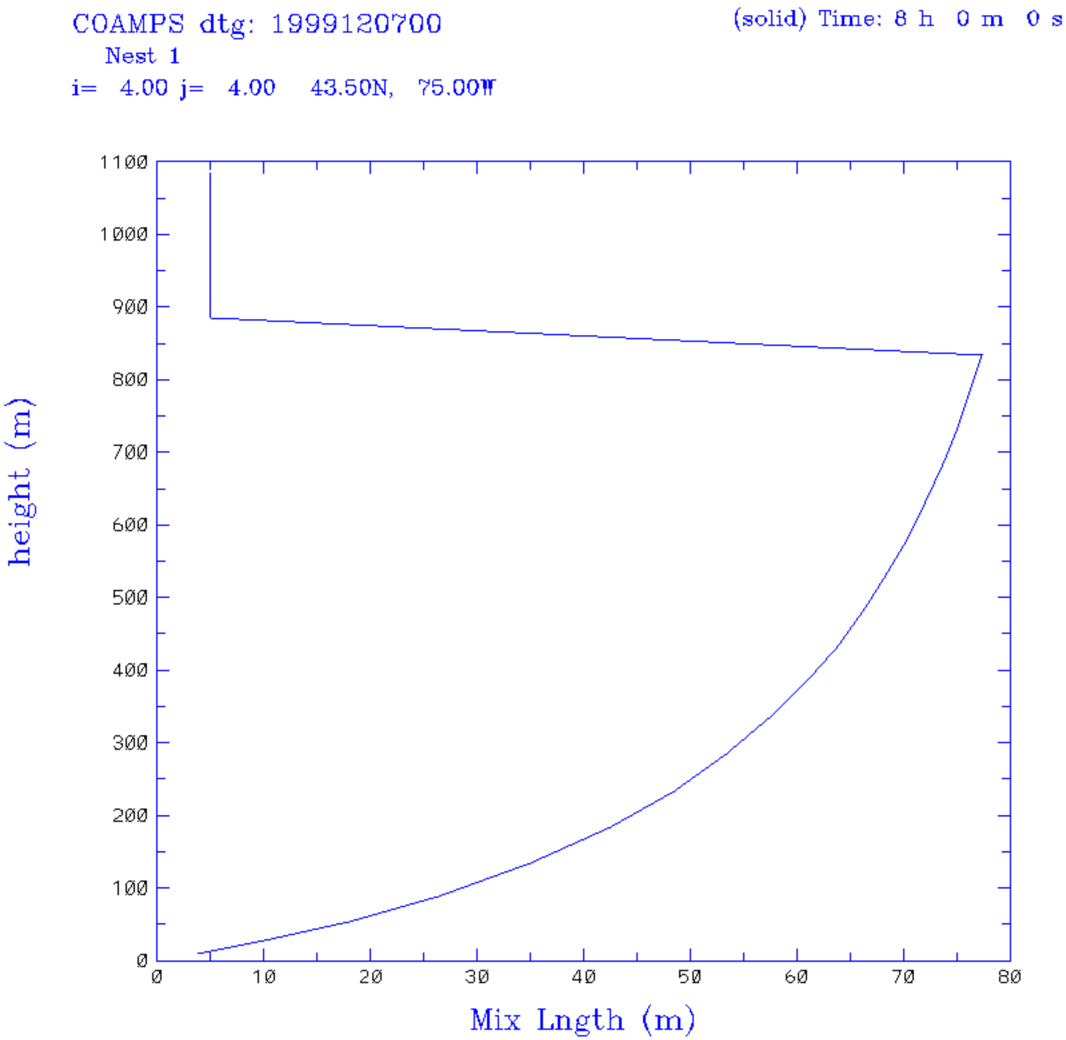
8 h forecast in a nocturnal marine stratus simulation

Turbulence Length Scale Formulation

- There are probably as many length scale formulations as there are models
- Many formulations use some function of boundary layer depth, which has some undesirable consequences
- COAMPS uses the von Karaman constant, the height, and an asymptotic value dependent on the vertical distribution of TKE:

$$l = \frac{\kappa z}{1 + \frac{\kappa z}{\lambda}}$$

Turbulence Length Scale



8 h forecast in a nocturnal marine stratus simulatio

Boundary Layer Depth and Counter-Gradient Term

- The boundary layer depth is difficult to quantify in numerical models
- COAMPS uses the elevation at which $Ri_f <= 0.25$
- Properties in the boundary layer are transported by large, turbulent eddies
- The net effect of this transport is to move things from high to low (down the gradient)
- In small regions, there may be local transport from low to high (counter to the gradient
- This cannot be accounted for by K-theory but requires a counter-gradient parameterization

Effect of Clouds

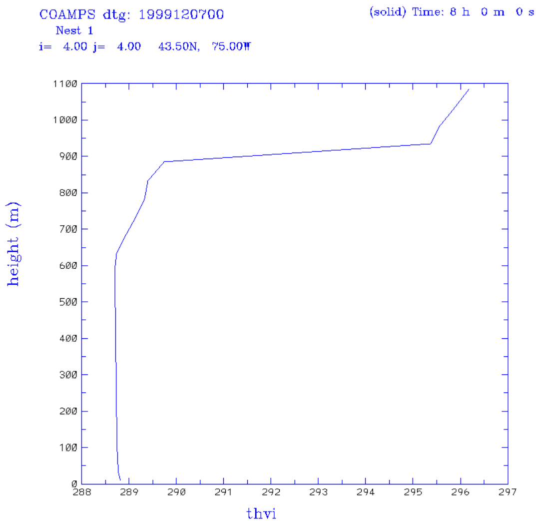
- The buoyancy term in the tke equation will be a source or sink of turbulence depending on stability
- In clear conditions, neutral stratification implies that the lapse rate is adiabatic and the virtual potential temperature is constant
- In cloudy air, neutral stratification implies that the lapse rate is moist adiabatic and virtual potential temperature is not constant
- The solution to this problem in COAMPS is to use two different temperature variables:
  - Virtual potential temperature in clear air
  - Liquid water potential temperature in clouds/fog

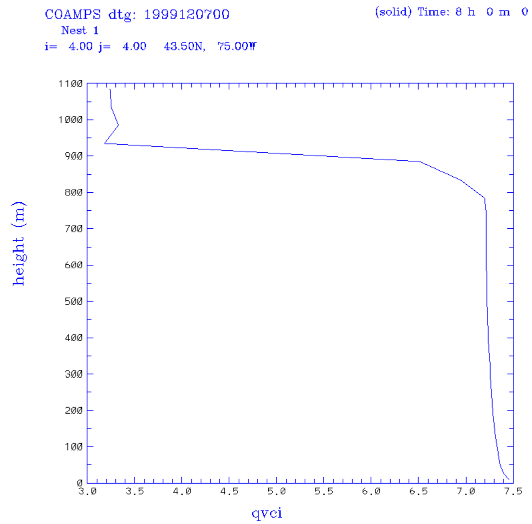
Effect of Clouds

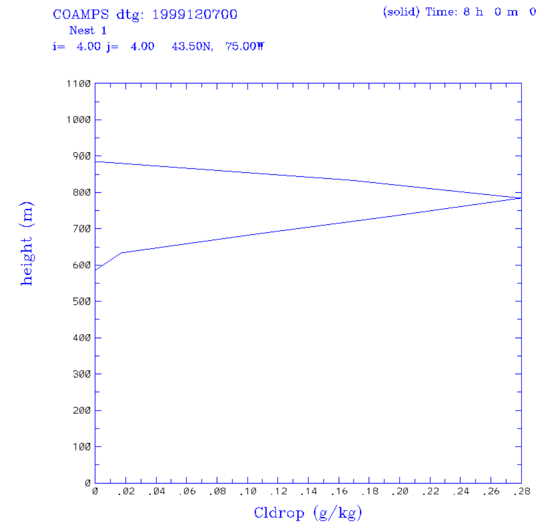
- The cloud/no cloud determination is based on cond, the heating/cooling due to condensation/evaporation
- If cond.le.0 at a particular grid point
  - There is no cloud and/or evaporation is occurring
  - The vertical temperature gradient is based on virtual potential temperature
- If cond.gt.0 at a particular grid point,
  - There is cloud/fog and/or condensation is occurring
  - The vertical temperature gradient is based on liquid water potential temperature

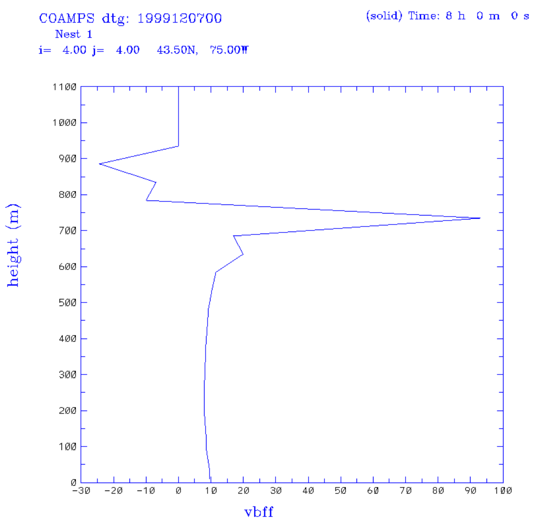
COAMPS 1-D Nighttime Stratus Simulation

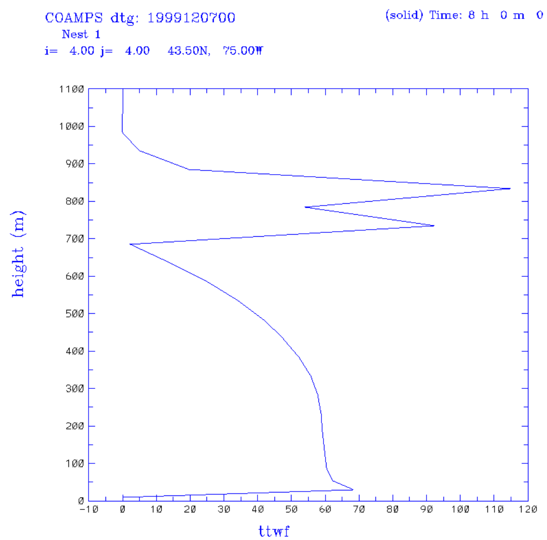
Modified afore.F

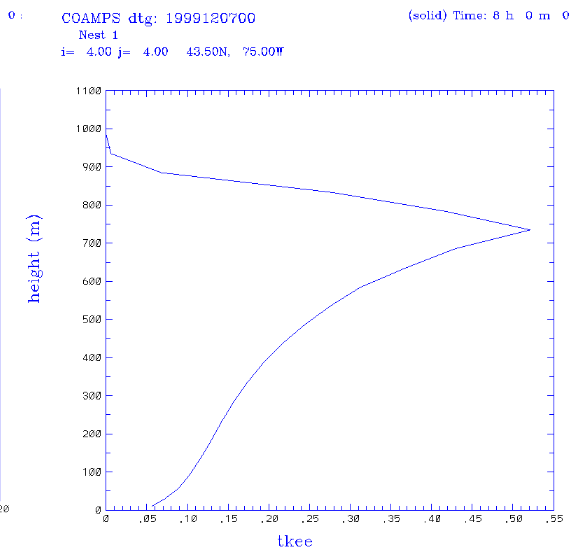




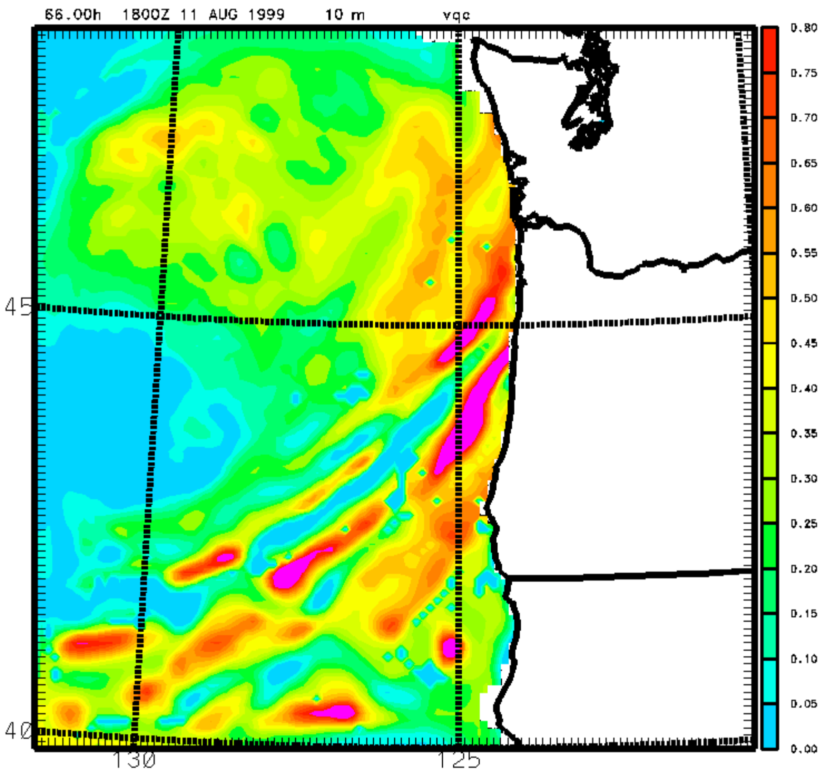


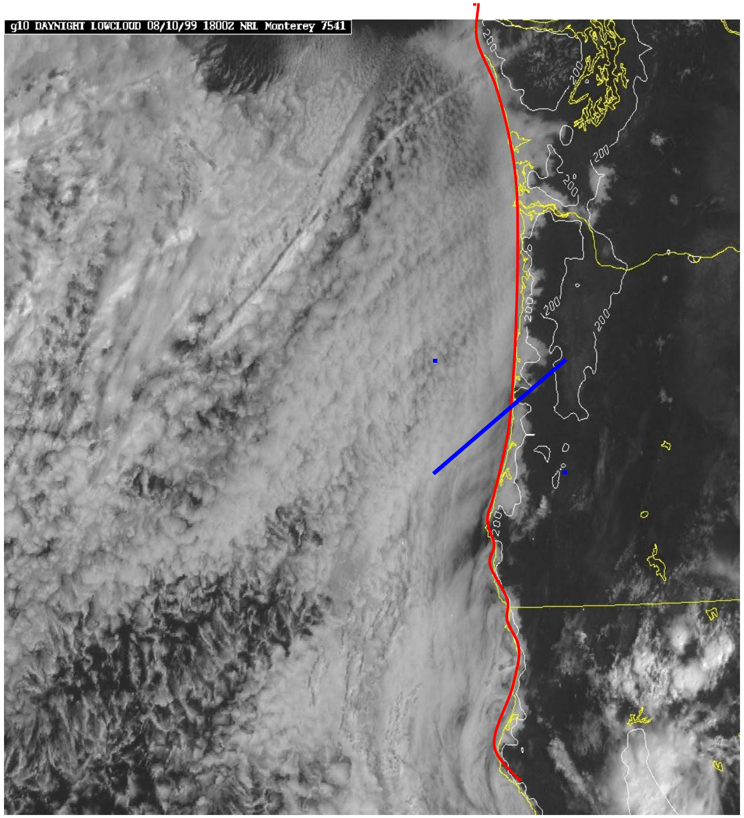




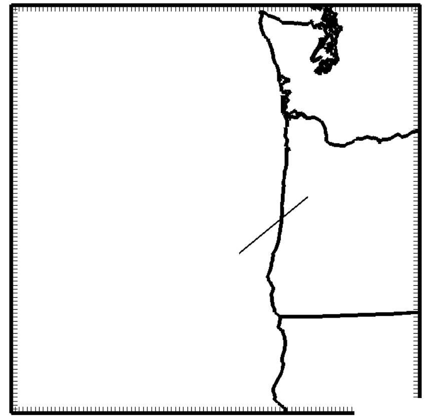


COAMPS Integrated Cloud Liquid Water (kg/m²)
18 UTC 11 June



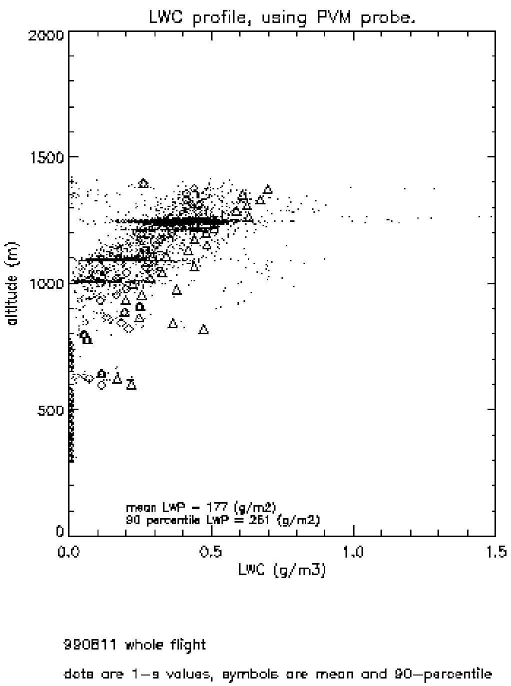


Aircraft vs COAMPS Cloud Liquid Water Content (kg/m³)
11 August 1999

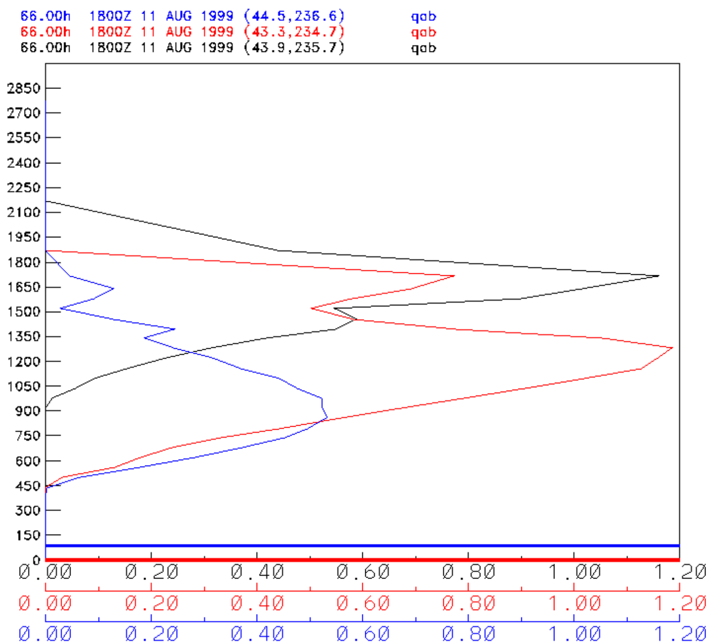


Aircraft Track

Aircraft LWC



COAMPS LWC



COAMPS Surface Layer Parameterization

- The surface layer parameterization uses the Louis (1979) scheme
- Polynomial functions of the bulk Richardson number are used to directly compute
  - surface sensible heat flux
  - surface latent heat flux
  - surface drag

$$Ri_B = \frac{gz\Delta\theta}{u^2\Theta}$$

COAMPS Surface Layer Parameterization

- Surface roughness is computed following the TOGA-COARE scheme

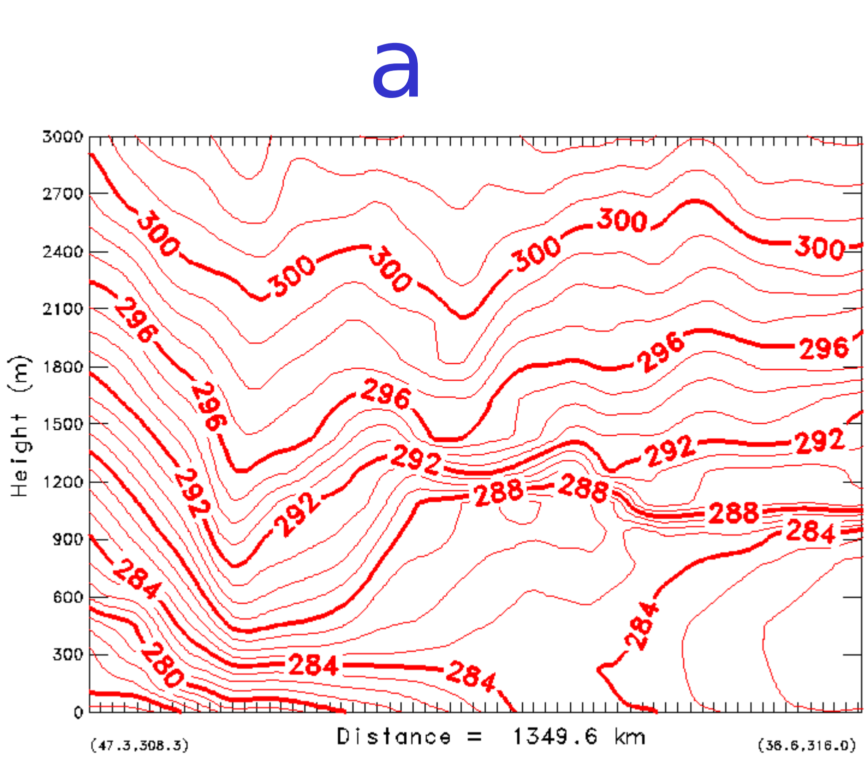
$$z_0 = c_0 \frac{u_*^2}{g} + c_\nu \frac{\nu}{u_*}$$

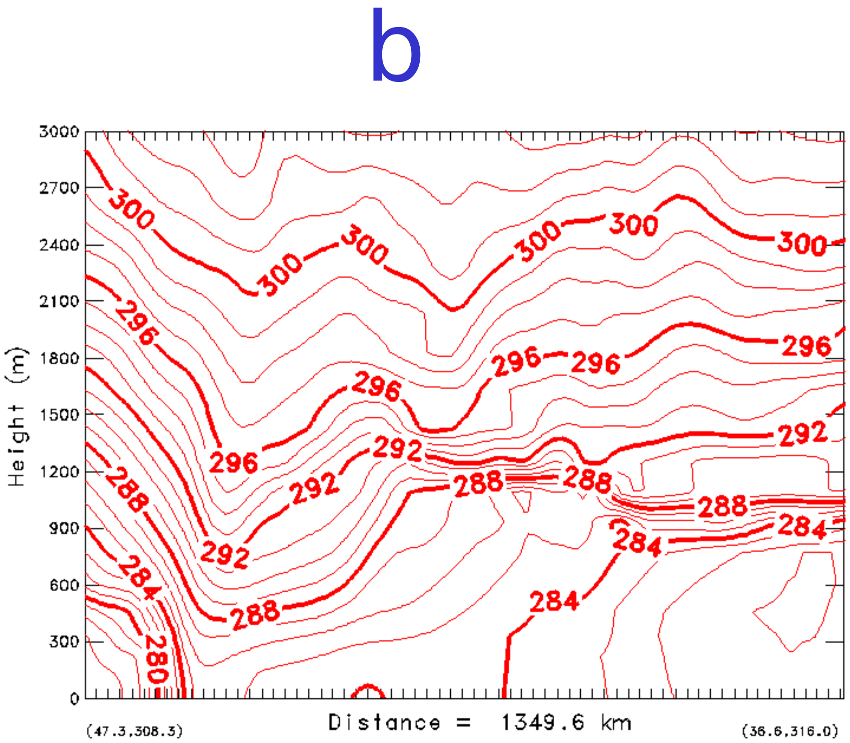
- A new parameterization is undergoing testing which is based on the TOGA-COARE scheme
  - Different functional forms for z_{0t} and z_{0q}
  - uses similarity theory directly
  - has polynomial approximation for stability function on the unstable side

Atmospheric Boundary Layer

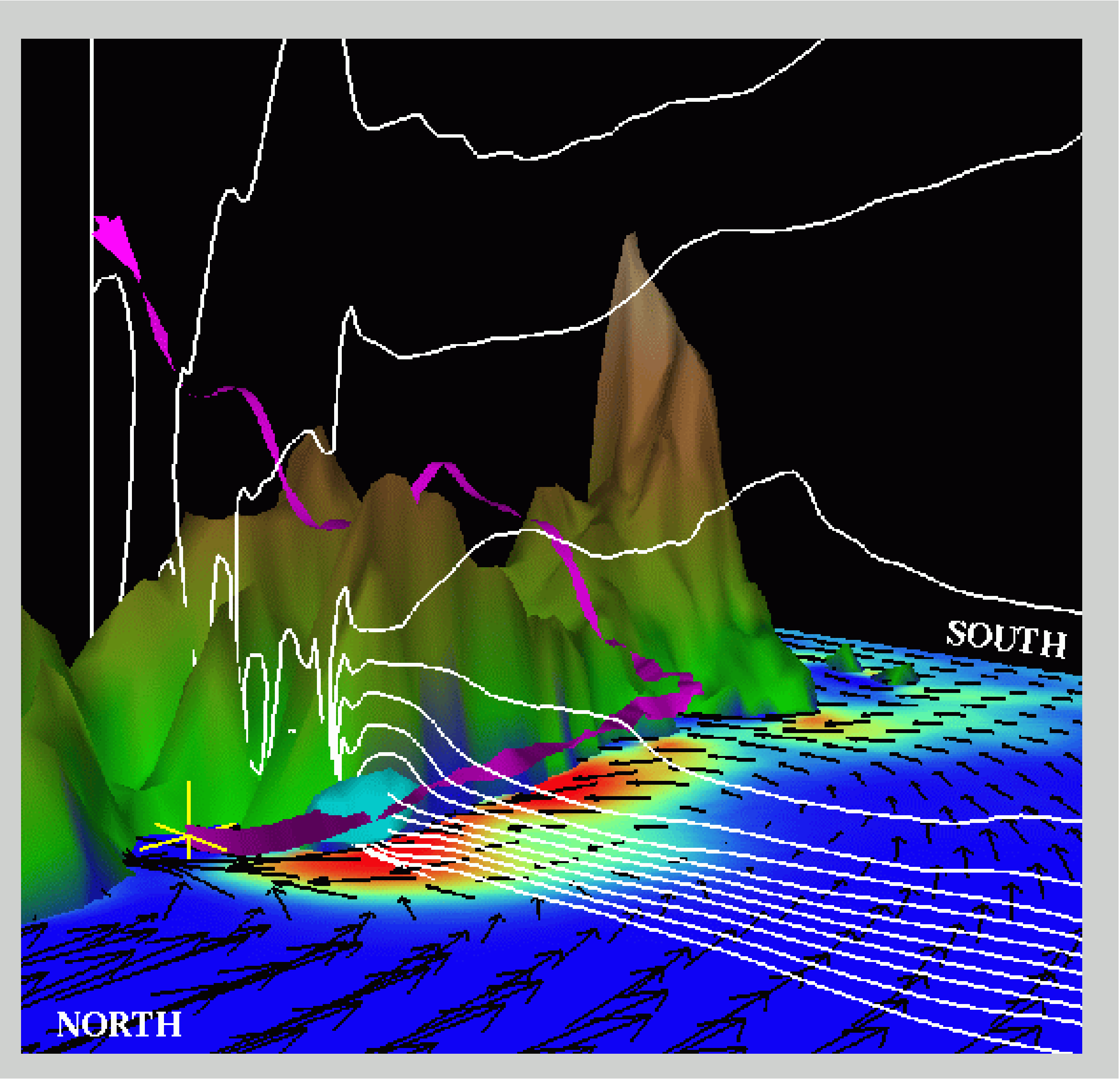
Mesoscale Circulations Impacted by boundary layer processes/parameterization

- Frontogenesis/Frontolysis induced by mesoscale distribution of surface sensible heat flux
- Frontogenesis induced by frictional convergence enhancing the pre-frontal updraft
- Coastally trapped wind reversals/Catalina Eddies
- Low-level jet interaction with stable marine boundary layer
- Sea Breezes





Potential temperature cross sections from COAMPS simulations of a cold front over the North Atlantic Ocea
(a) with and (b) without surface sensible heat flux



COAMPS Simulation of a coastally trapped wind reversa

Atmospheric Boundary Layer Modeling

Schemes used in operational models:

– ECMWF	1st order closure
– NOGAPS	Louis
– NCEP RUC	Mellor-Yamada L3.0
– COAMPS	Mellor-Yamada L2.5
– MM5	Mellor-Yamada L2.5